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The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

This project has supported the analysis and design of large-scale wireless networks for army applications, including information dissemination algorithms for fixed wireless and mobile wireless networks, energy management algorithms for sensor networks, resilience of wireless networks to virus epidemics, network coding capacity of wireless networks, coding for mobile wireless networks, polar coding for multiple-access networks, and the capacity of wireless relay networks. The project has supported the education and research activities of a

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Sensor networks, network coding, random geometric graphs, wireless networks, network resilience, connectivity, information dissemination, mobile wireless networks, polar codes, wireless relay networks, cascading failure, power networks

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UU	UU	UU	UU		Edmund Yeh
					19b. TELEPHONE NUMBER 203-432-7271

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Report Title

Final Report for "Percolation Processes and the Design of Large-Scale Wireless Networks"

ABSTRACT

This project has supported the analysis and design of large-scale wireless networks for army applications, including information dissemination algorithms for fixed wireless and mobile wireless networks, energy management algorithms for sensor networks, resilience of wireless networks to virus epidemics, network coding capacity of wireless networks, coding for mobile wireless networks, polar coding for multiple-access networks, and the capacity of wireless relay networks. The project has supported the education and research activities of a postdoctoral fellow and a graduate student.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received	Paper
2012/05/30 1 14	Edmund M. Yeh, Zhenning Kong. Resilience to Degree-Dependent and Cascading NodeFailures in Random Geometric Networks, IEEE Transactions on Information Theory, (11 2010): 5533. doi:

TOTAL: 1

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received	Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

1. "Polar Codes for Multiple Access Channels." Information Theory and Applications Workshop, University of California at San Diego, February 8, 2011.

2. "Cascading Failure in Power Networks: a Percolation-Based Analysis." DIMACS Workshop on Algorithmic Decision Theory for the Smart Grid, New Brunswick, NJ, October 26, 2010.

3. "Connectivity, Mobility, and Information Dissemination." Information Theory and Applications Workshop, University of California at San Diego, February 4, 2010.

4. "Network Science: Information Spread, Epidemics, Mobility and Cascading Failures." Workshop on \Network Science: New Directions in Control Systems," IEEE Conference on Decision and Control (CDC), Shanghai, China, December 15, 2009.

5. "Information Dissemination in Mobile Wireless Networks." Workshop on Mathematical Modelling and Analysis of Wireless Networks, Toronto, Canada, May 8, 2008.

Number of Presentations: 5.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper
2012/05/30 1(10	Elona Erez, Yun Xu, Edmund M. Yeh. Coding for the Deterministic Network Model, Information Theory and Applications Workshop. 2010/01/30 18:00:00, . : ,
2012/05/30 1(3	Edmund M. Yeh, Zhenning Kong. Percolation Processes and Wireless Network Resilience, Information Theory and Applications Workshop. 2008/01/26 18:00:00, . : ,
2012/05/30 0(7	Zhenning Kong, Edmund M. Yeh. Information Dissemination in Large-Scale WirelessNetworks with Unreliable Links, International Wireless Internet Conference (Wicon). 2008/11/16 18:00:00, . : ,

TOTAL: 3

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper
2012/05/30 1' 15	Hongda Xiao, Edmund M. Yeh. Cascading Link Failure in the Power Grid:A Percolation-Based Analysis, IEEE International Workshop on Smart Grid Communications. 2011/06/04 18:00:00, . : ,
2012/05/30 1(13	Elona Erez, Yun Xu, Edmund M. Yeh. Coding for the Deterministic Network Model, Allerton Conference on Communication, Control, and Computing. 2010/09/28 18:00:00, . : ,
2012/05/30 1(11	Zhenning Kong, Edmund M. Yeh, Emina Soljanin. Coding Improves the Throughput-Delay Trade-off in Mobile Wireless Networks, IEEE International Symposium on Information Theory. 2009/06/27 18:00:00, . : ,
2012/05/30 0(9	Zhenning Kong, Edmund M. Yeh. Wireless Network Resilience to Degree-Dependentand Cascading Node Failures, Workshop on Spatial Stochastic Models in Wireless Networks (SpaSWiN). 2009/06/25 18:00:00, . : ,
2012/05/30 0(6	Zhenning Kong, Edmund M. Yeh. On the Latency for Information Dissemination in MobileWireless Networks, ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc). 2008/05/25 18:00:00, . : ,
2012/05/30 0(4	Zhenning Kong, Edmund M. Yeh. Connectivity and Latency in Large-Scale WirelessNetworks with Unreliable Links, Conference on Computer Communications (Infocom). 2008/04/14 18:00:00, . : ,
2012/05/30 0(2	Zhenning Kong, Salah A. Aly, Emina Soljanin, Edmund M. Yeh, Andreas Klappenecker. Network Coding Capacity of Random Wireless Networks under a Signal-to-Interference-and-Noise-Ratio Model, llerton Conference on Communication, Control, and Computing. 2007/09/25 18:00:00, . : ,
2012/05/30 0(1	Zhenning Kong, Edmund M. Yeh. Distributed Energy Management Algorithm for Large-Scale Wireless Sensor Networks, Eighth ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc). 2007/09/08 18:00:00, . : ,

TOTAL: 8

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received	Paper
2012/05/30 1(16	Eren Sasoglu, Emre Telatar, Edmund M. Yeh. Polar codes for the two-user multiple-access channel, SUBMITTED TO IEEE TRANSACTIONS ON INFORMATION THEORY (06 2010)
2012/05/30 1(12	Zhenning Kong, Edmund M. Yeh, Emina Soljanin. Coding Improves the Throughput-Delay Trade-off in Mobile Wireless Networks, SUBMITTED TO IEEE TRANSACTIONS ON INFORMATION THEORY (03 2010)
2012/05/30 0{ 8	Zhenning Kong, Edmund M. Yeh. Connectivity and Information Dissemination inLarge-Scale Wireless Networks with Dynamic Links, SUBMITTED TO IEEE TRANSACTIONS ON INFORMATION THEORY (02 2009)
2012/05/30 0{ 5	Zhenning Kong, Salah A. Aly, Emina Soljanin, Edmund M. Yeh, Andreas Klappenecker . Network Coding Capacity of Random Wireless Networks under a SINR Model, SUBMITTED TO IEEE TRANSACTIONS ON INFORMATION THEORY (04 2008)

TOTAL: 4

Number of Manuscripts:

Books

Received Paper

TOTAL:

Patents Submitted

Patents Awarded

Awards

1. Humboldt Research Fellowship from Alexander von Humboldt Foundation, 2010.

2. Invited to National Science Foundation Future Internet Architecture Summit, 2009.

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Yun Xu	0.50	
Zhenning Kong	0.00	
Hongda Xiao	0.00	
FTE Equivalent:	**0.50**	
Total Number:	**3**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Elona Erez	0.19
FTE Equivalent:	**0.19**
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Edmund Yeh	0.03	
FTE Equivalent:	**0.03**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	Discipline
Jason Kaufman	0.00	Electrical Engineering
Marjan Firouzgar	0.00	Electrical Engineering
FTE Equivalent:	**0.00**	
Total Number:	**2**	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 2.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 2.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 1.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 2.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 1.00

Names of Personnel receiving masters degrees

NAME	
Yun Xu	
Total Number:	**1**

Names of personnel receiving PHDs

NAME	
Zhenning Kong	
Total Number:	**1**

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Please see attached file.

Technology Transfer

Final Report

1 Statement of Problems Studied

The major problems investigated as a part of this project include:

1. Develop distributed energy management algorithms for sensor networks which enhance energy efficiency while maintaining network connectivity.

2. Characterize connectivity and delay for information dissemination algorithms in fixed wireless networks with fading.

3. Characterize connectivity and delay for information dissemination algorithms in mobile wireless networks.

4. Analyze resilience to dependent and cascading node failures in large-scale wireless networks.

5. Analyze resilience to dependent and cascading link failures in large-scale electrical power networks.

6. Characterize the capacity of large-scale interference-limited wireless networks under network coding.

7. Improve the fundamental throughput-delay tradeoff in mobile wireless netoworks.

8. Develop low-complexity codes to achieve the capacity of wireless relay networks.

9. Develop polar coding schemes to achieve the capacity of multiple-access channels with low complexity.

2 Summary of Most Important Results

Over the past four years covered by this grant, the PI has made significant progress in solving the major research problems outlined above.

Distributed Energy Management for Wireless Sensor Networks - In battery-constrained wireless sensor networks, it is important to employ effective energy management while maintaining some level of network connectivity. Viewing this problem from a percolation-based connectivity perspective, the PI has developed a fully distributed energy management algorithm for large-scale wireless sensor networks. This algorithm allows each sensor to probabilistically schedule its own activity based on its node degree. This mechanism is modelled by a degree-dependent dynamic site percolation process on random geometric graphs. The PI has specified the conditions under which

the resulting network is guaranteed to be percolated for all time. The PI has further studied the delay performance of the proposed energy management algorithm by modelling the problem as a degree-dependent first passage percolation process on random geometric graphs.

Information Dissemination in Fixed Wireless Networks with Fading - The PI has studied connectivity and transmission latency in wireless networks with unreliable links from a percolation-based perspective. The PI first examined static models, where each link of the network is functional (active) with some probability, independently of all other links, where the probability may depend on the distance between the two nodes. The PI has obtained analytical upper and lower bounds on the critical density for phase transition in this model. The PI then examines dynamic models, where each link is active or inactive according to a Markov on- off process. The PI shows that a phase transition also exists in such dynamic networks, and the critical density for this model is the same as the one for static networks under some mild conditions. Furthermore, due to the dynamic behavior of links, a delay is incurred for any transmission even when propagation delay is ignored. The PI has studied the behavior of this transmission delay and showed that the delay scales linearly with the Euclidean distance between the sender and the receiver when the network is in the subcritical phase, and the delay scales sub-linearly with the distance if the network is in the supercritical phase.

Information Dissemination in Mobile Wireless Networks - In wireless networks, node mobility may be exploited to assist in information dissemination over time. The PI has analyzed the latency for information dissemination in large-scale mobile wireless networks. To study this problem, the PI maps a network of mobile nodes to a network of stationary nodes with dynamic links. The PI then uses results from percolation theory to show that under a constrained i.i.d. mobility model, the scaling behavior of the latency falls into two regimes. When the network is not percolated (subcritical), the latency scales linearly with the initial Euclidean distance between the sender and the receiver; when the network is percolated (supercritical), the latency scales sub-linearly with the distance.

Resilience to Dependent and Cascading Failures in Random Geometric Networks - The PI has studied the problem of resilience to node failures in large-scale networks modelled by random geometric graphs. Adopting a percolation-based view, the PI investigates the ability of the network to maintain global communication in the face of dependent node failures. The PI examines degree-dependent site percolation processes on random geometric graphs, and obtain the first known analytical conditions for the existence and non-existence, respectively, of a large connected component of operational network nodes after degree-dependent node failures. In electrical power networks or wireless communication and computing networks, cascading failure from power blackouts or virus epidemics may result from a small number of initial node failures triggering global failure events affecting the whole network. Using a simple but descriptive model, the PI shows that the cascading failure problem is equivalent to a degree-dependent percolation process. The PI obtains the first analytical conditions for the occurrence and non-occurrence of cascading failures, respectively, in large-scale networks with geometric constraints.

Cascading Link Failure in the Power Grid - Large-scale power blackouts caused by cascading failure are inflicting enormous socioeconomic costs. The PI has studied the problem of cascading link failures in power networks modelled by random geometric graphs from a percolation-based viewpoint. To reflect the fact that links fail according to the amount of power flow going through

them, the PI introduces a model where links fail according to a probability which depends on the number of neighboring links. The PI devises a mapping which maps links in a random geometric graph to nodes in a corresponding dual covering graph. This mapping enables the PI to obtain the first-known analytical conditions on the existence and non-existence of a large component of operational links after degree-dependent link failures. Next, the PI presents a simple but descriptive model for cascading link failure, and uses the degree-dependent link failure results to obtain the first-known analytical conditions on the existence and non-existence of cascading link failures.

Network Coding Capacity of Random Wireless Networks - The PI has studied the network coding capacity for random wireless networks. Previous work on network coding capacity for random wired and wireless networks have focused on the case where the capacities of links in the network are independent. In this work, the PI considers a more realistic model, where wireless networks are modeled by random geometric graphs with interference and noise. In this model, the capacities of links are not independent. By employing coupling and martingale methods, the PI shows that, under mild conditions, the network coding capacity for random wireless networks still exhibits a concentration behavior around the mean value of the minimum cut. Simulation results confirm our theoretical predictions.

Throughput-Delay Tradeoff in Mobile Wireless Networks - The PI has studied the throughput-delay performance tradeoff in large-scale wireless ad hoc networks. It has been shown that the per source-destination pair throughput can be improved from $\Theta(1/\sqrt{n \log n})$ to $\Theta(1)$ if nodes are allowed to move and a 2-hop relay scheme is employed. The price paid for such an improvement on throughput is large delay. Indeed, the delay scaling of the 2-hop relay scheme is $\Theta(\sqrt{n \log n})$ under the random walk mobility model. In this paper, we employ coding techniques to improve the throughput-delay trade-off for mobile wireless networks. For the random walk mobility model, the PI's results improve the delay from $\Theta(\sqrt{n \log n})$ to $\Theta(n)$ by employing Reed-Solomon codes. The PI's new approach maintains the diversity gained by mobility while decreasing the delay.

Coding for Wireless Relay Networks - The capacity of multiuser networks has been a long-standing problem in information theory. Recently, Avestimehr et al. have proposed a deterministic network model to approximate wireless networks. For multicast, they have shown that the capacity for the deterministic model is equal to the minimal rank of the incidence matrix of a certain cut between the source and any of the sinks. Their proposed code construction, however, is not guaranteed to be efficient and may potentially involve an infinite block length. The PI has developed an efficient linear code construction for the deterministic wireless multicast relay network model. Unlike several previous coding schemes, the PI does not attempt to find flows in the network. Instead, the new construction maintains an invariant where it is required that at each stage of the code construction, certain sets of codewords are linearly independent.

Polar Coding for Multiple-access Networks - Achieving the fundamental capacity limits of noisy communication channels with low complexity coding schemes has been a major challenge for over 60 years. Recently, a revolutionary coding construction, called Polar coding, has been shown to provably achieve the Shannon capacity of discrete memoryless single-user channels. Whereas a number of practical coding constructions (e.g. Turbo codes and Low Density Parity Check codes) can empirically approach the capacity of single-user communication channels, there is still an absence of good practical coding schemes for multi-user communication networks. In recent work, the PI has invented a polar coding scheme which can achieve some of the optimal transmission

rates for multiple-access (uplink) networks. The encoding and decoding complexity of the code is $O(n \log n)$ with n being the block length, and the block error probability is roughly $O(2^{-\sqrt{n}})$. The new coding construction is one of the first low-complexity coding schemes which can provably achieve Shannon capacity in multi-user communication networks.